Photon + jet measurements at D0

Dmitry Bandurin

Kansas State University

on behalf of D0 Collaboration

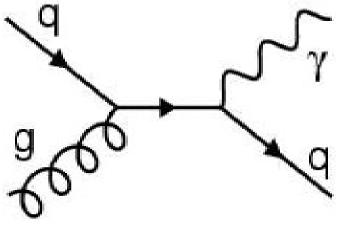
CIPANP 2009

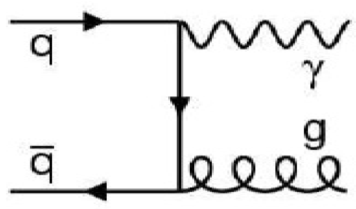
26-May-2009

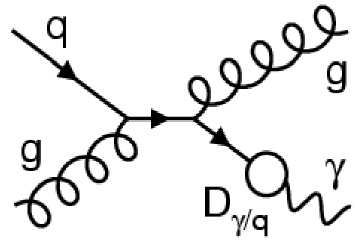
Outline

- D0 at Tevatron and photon+jet physics
- Inclusive photon Production Cross Section
- Photon plus Jets Production Cross Section
- Photon plus Heavy Flavor Production Cross Section
- Double Parton Scattering
- Summary

Motivations







▶ Photons have a good energy resolution and almost free from the fragmentation related systematics.

▶ Direct photons come unaltered from the hard scattering

⇒ Allows a direct probe of hard scattering dynamics

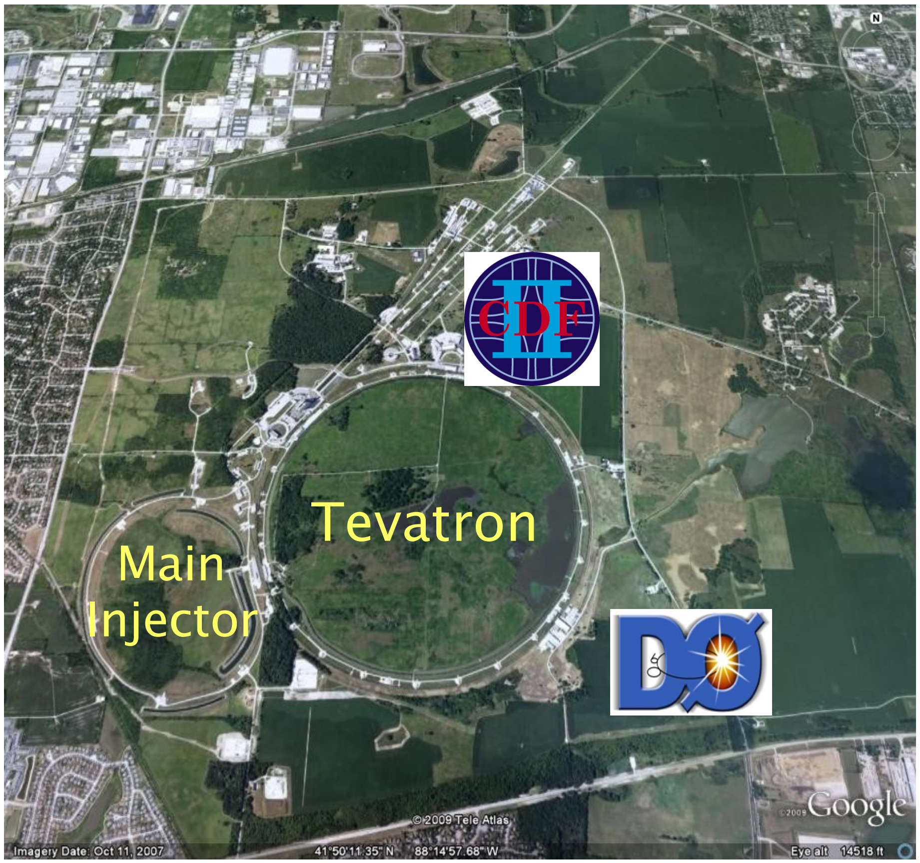
- Precision tests of QCD
- Probes of gluon and b, c -quark PDFs and b/c fragmentations
- Tests of spatial distribution of partons in the proton and understanding of multi-jet production mechanism.

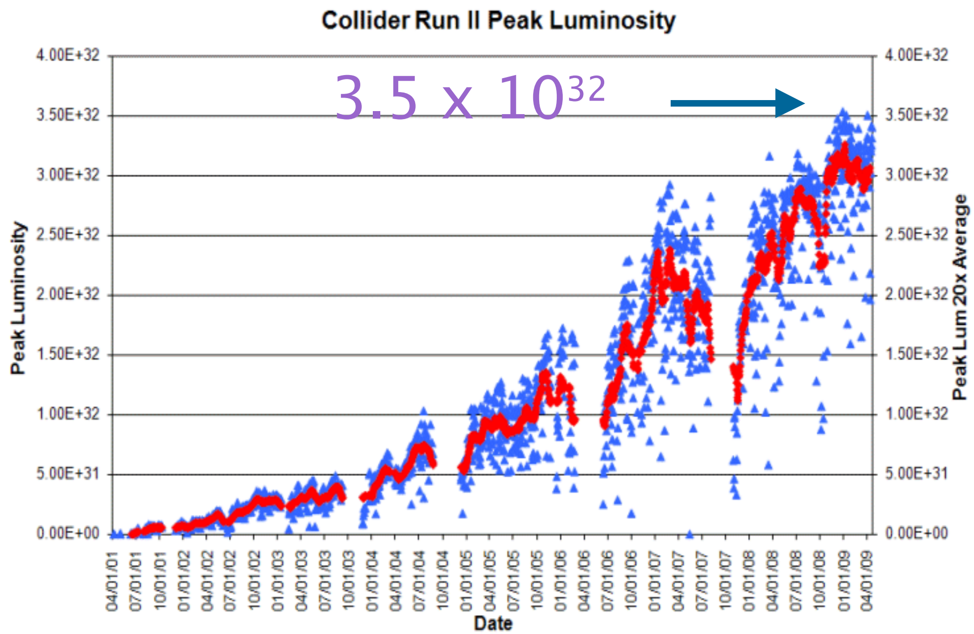
- Photon+jets are important background to many physics processes (e.g. H $\rightarrow \gamma\gamma$; G $\rightarrow$ $ee,\gamma\gamma$; technicolor ω_T, $a_T \rightarrow \gamma\pi$ with $\pi \rightarrow$ bb, bc)

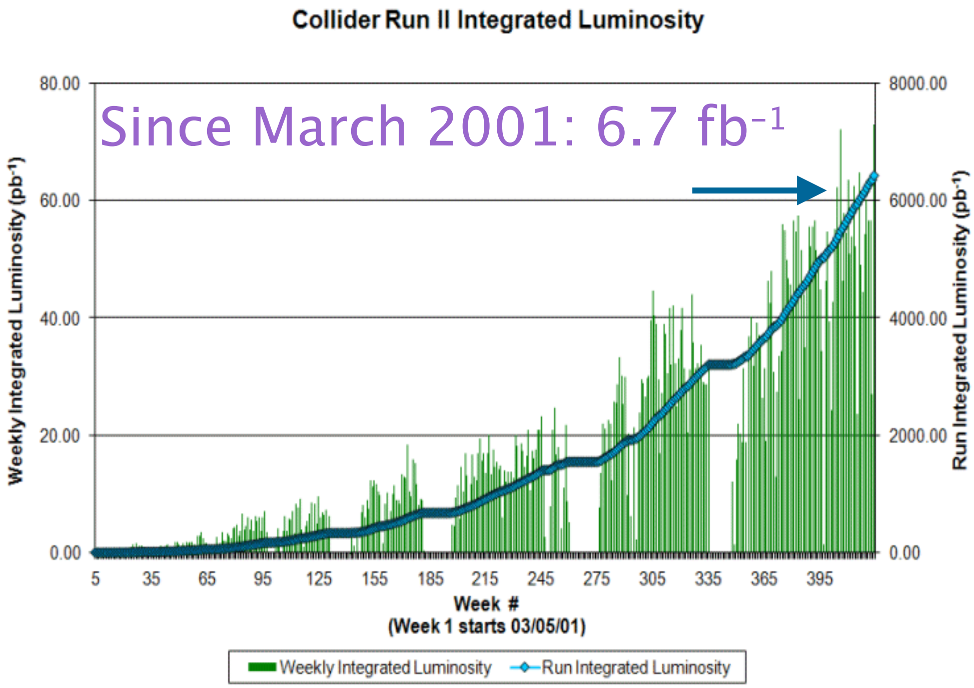
- Understanding double(triple) parton scattering mechanism is pre-required in detecting many rare processes, searches for new physics.

Fermilab Tevatron Run II

- $\sqrt{s}$ = 1.96 TeV
- Peak Luminosity: 3.5×10^{32} $cm^{-2}s^{-1}$
- About 6.7 fb^{-1} delivered
- Experiments typically collect data with 80–90% efficiency



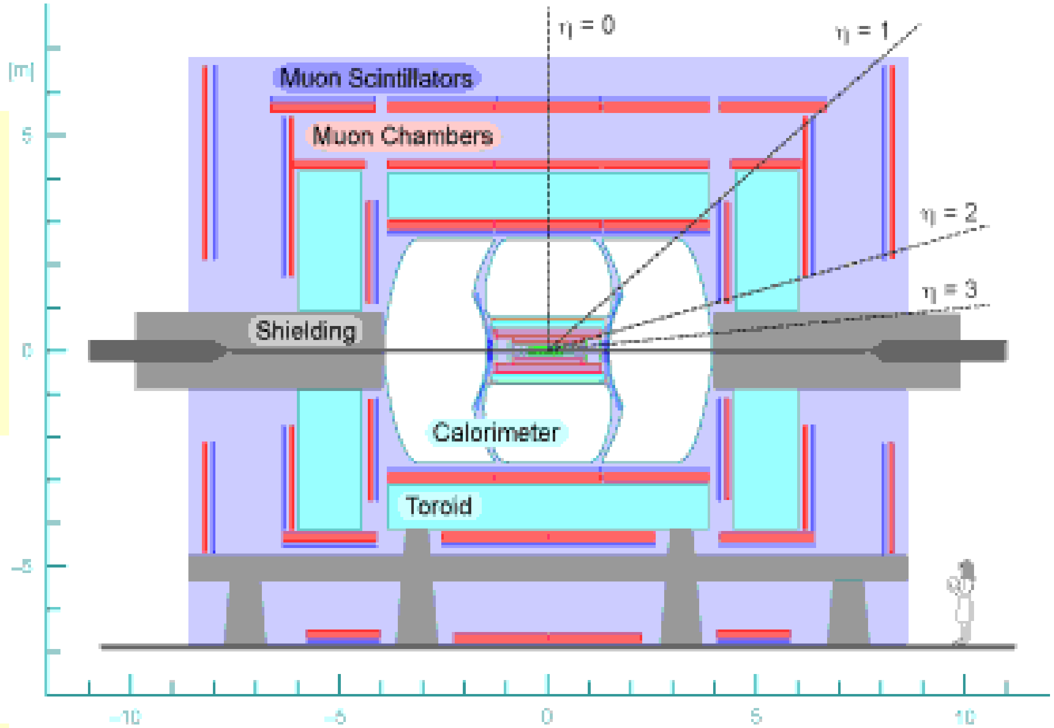




D0 detector

Three main systems

- Tracker (silicon and scintillating fiber)
- Calorimeter (LAr/U, some scintillator)
- Muon chambers and scintillators

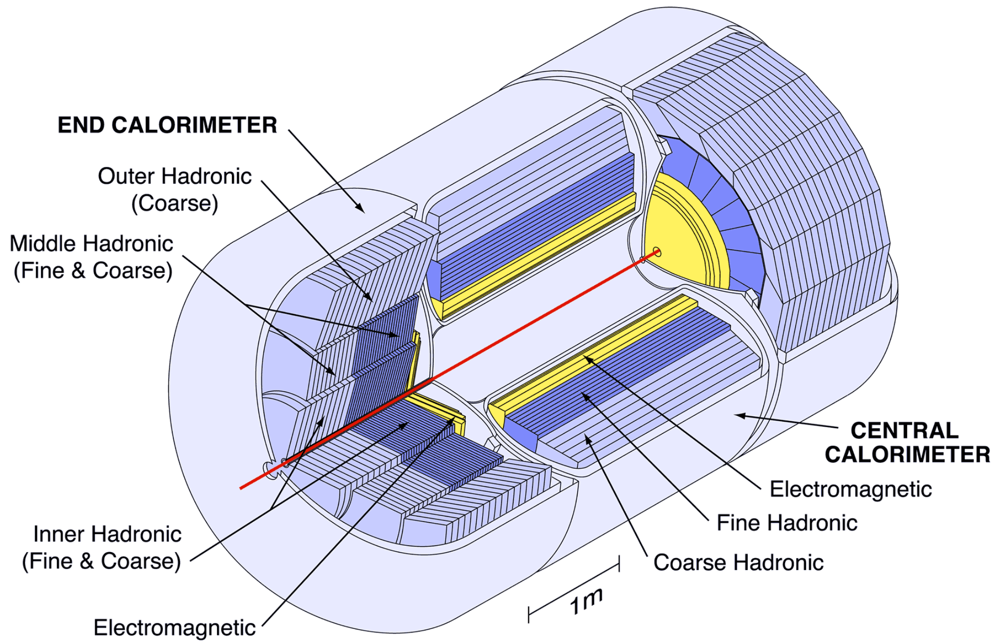


D0 calorimeter

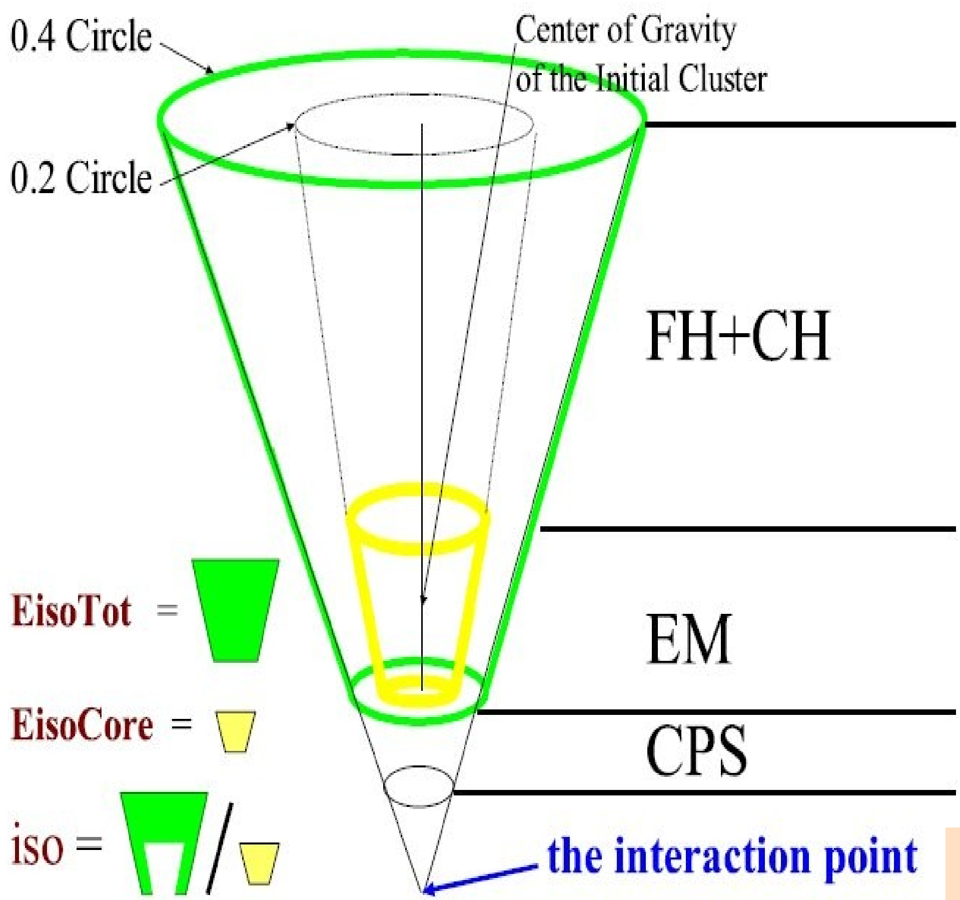
✓ The most important detector for photon and jet measurements

✓ Three main subregions: Central ($|\eta|<1.1$), Intercryostat ($1.1<|\eta|<1.5$) and End calorimeters ($1.5 < |\eta| < 4.2$)

✓ Liquid Argon/Uranium calorimeter:
- Stable response, good resolution
- Partially compensating (e/h ~1)



Photon Identification



- EM shower in calorimeter
  $\rightarrow \gamma$ candidate
- No associated track
- Isolation criteria

  Define $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

  $Isol = \frac{E_{tot}(R=0.4) - E_{EM}(R=0.2)}{E_{EM}(R=0.2)} < 0.07$
- EM fraction > 96%
- dR(γ,jet) > 0.7 (cone jet,R=0.7)

Background estimation

Origin: EM jets composed of $\pi^0, \eta, K_s^0, \omega$ mesons surrounded by (soft) hadrons

Tool: Photon ANN based on calorimeter and track information

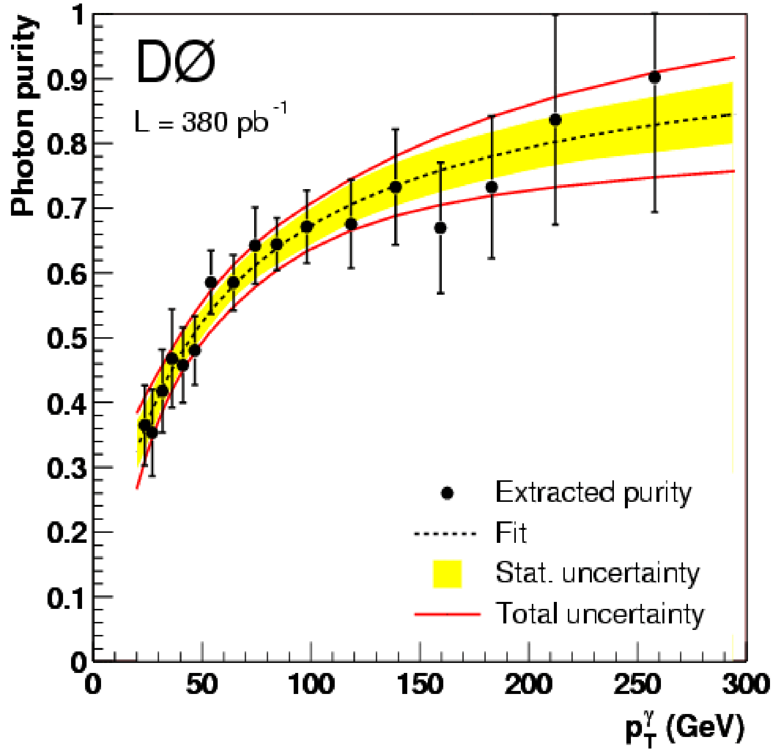
Inclusive isolated photon production

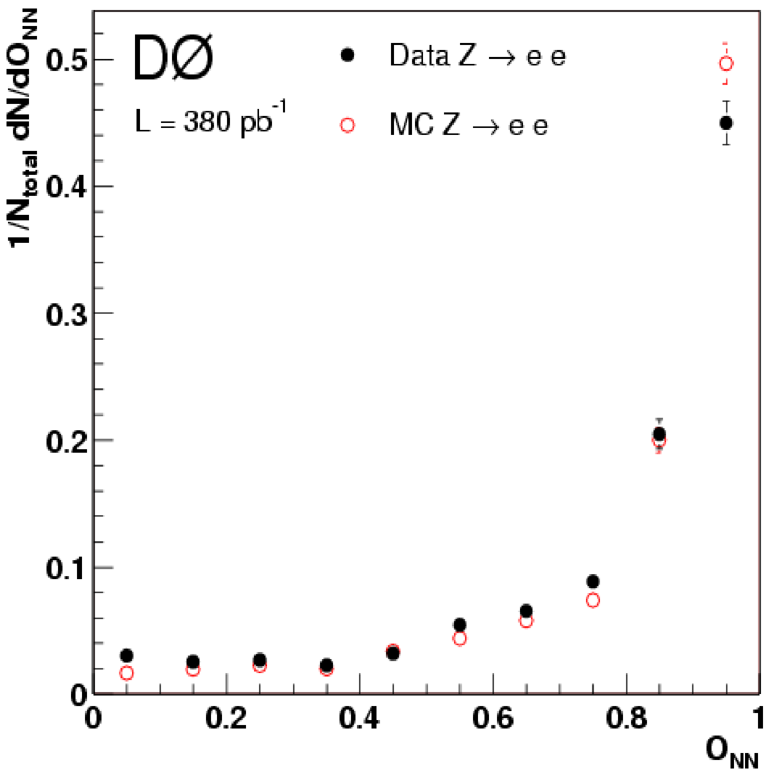
D0 Collab., Phys. Lett. B 639, 151 (2006)

L = 380 pb^{-1}

Main selection criteria:

- p_T^γ > 23 GeV and $|\eta| < 0.9$
- Isol < 0.10, EM frac > 0.95, O_{NN} > 0.5
- Missing Et < 0.7 p_T^γ (cosmics, W $\rightarrow$ eν)

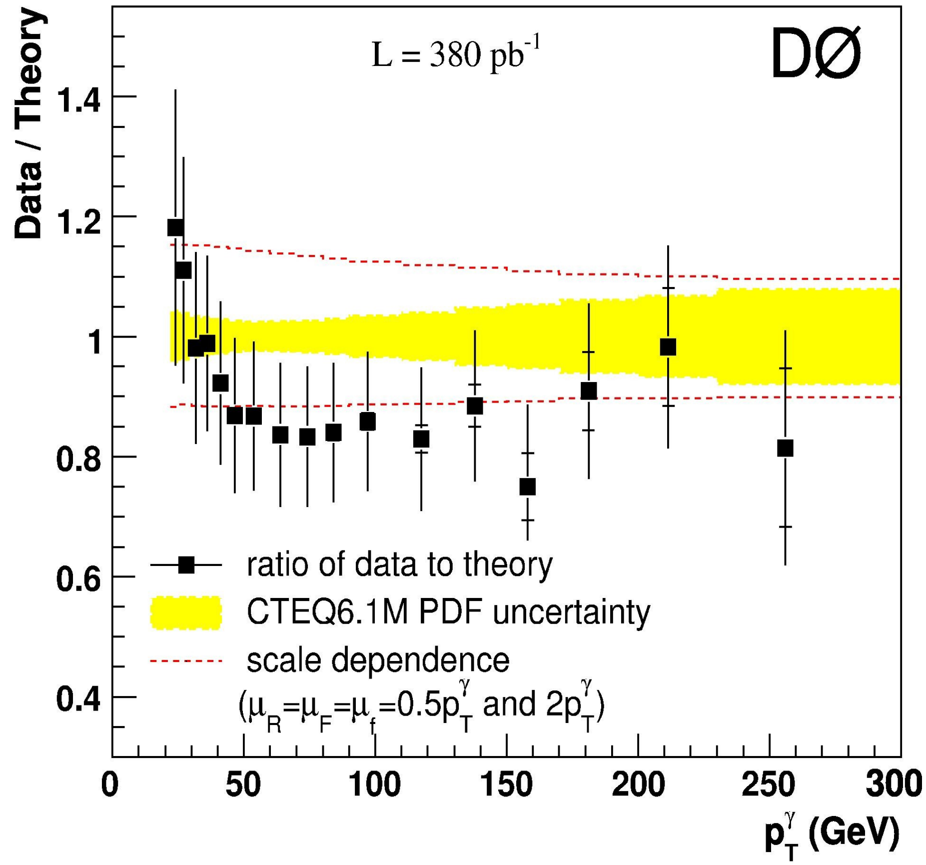


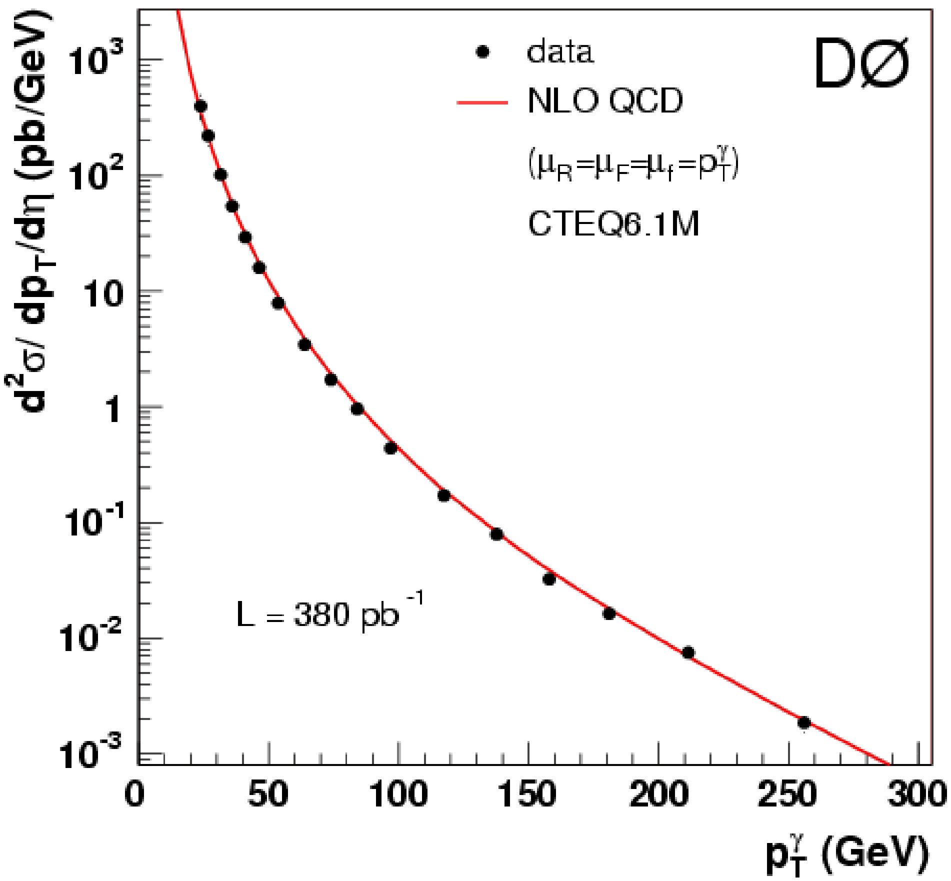


- Neural Net (NN) is trained to discriminate photons from EM jets
- EM shower shape + track pT sum is input to NN
- Tested on Z $\rightarrow$ ee in data/MC
- Photon purity obtained from fit of NN output for MC signal and EM jets to data

Inclusive isolated photon production

- Plotted: p_T^γ - weighted bin centers
- Large range: 23 –300 GeV
- QCD test at >5 orders of magnitude of cross section variation
- Compared to JetPhoX (NLO QCD)
- BFG photon fragmentation functions





Data-to-theory comparison

- Results are consistent with theory
- Variation/Shape similar to former observations (UA2, CDF)

⇒ suggests more detailed check

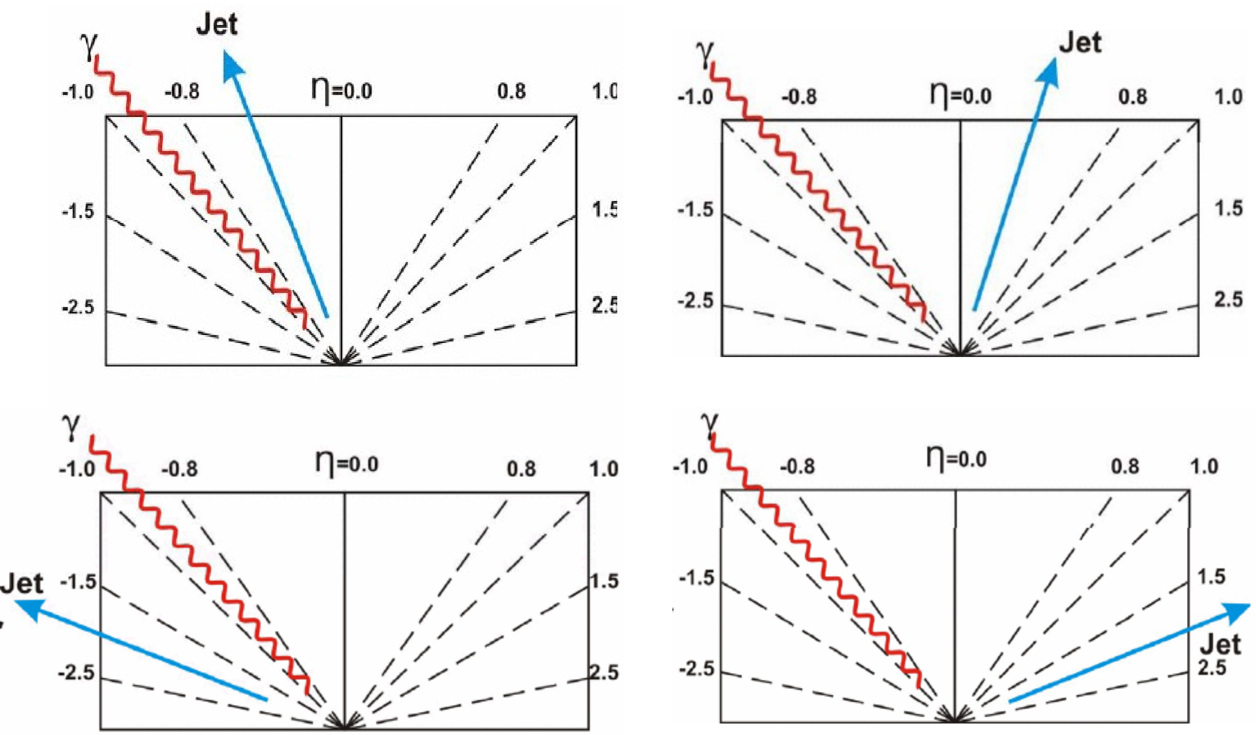
Inclusive photon+jet production

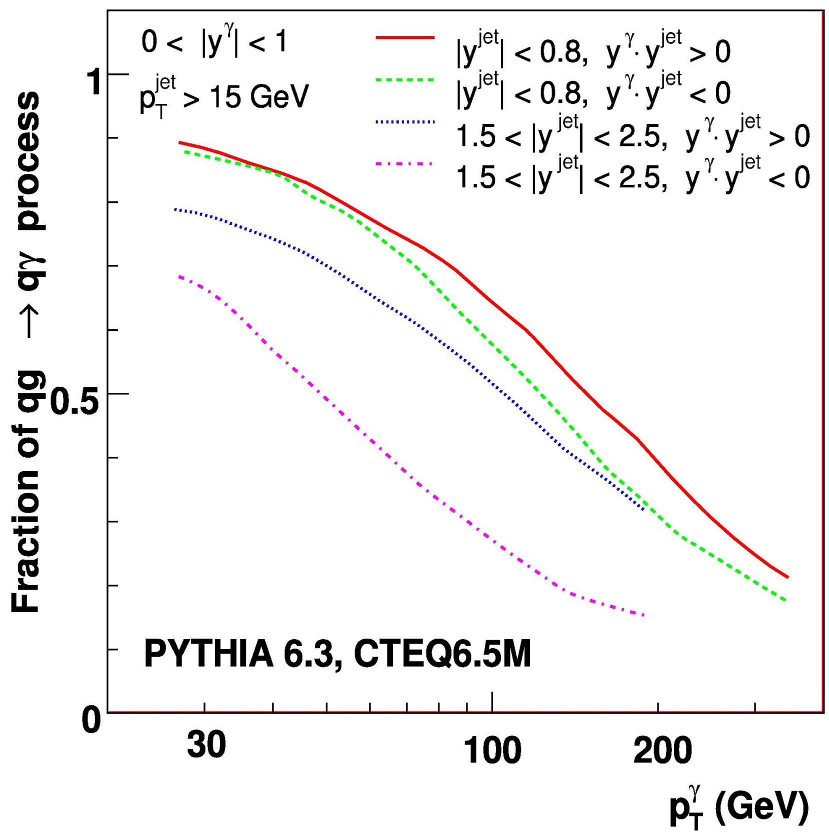
$$\frac{d^3\sigma}{dp_T^\gamma \, d\eta^\gamma \, d\eta^{jet}}$$

D0 Collab., Phys. Lett. B 666, 2435 (2008)

L = 1 fb^{-1}

- Tag photon and jet, ⇒ full control of the 2-body kinematics in the final state
- Measurement done in the four photon-jet rapidity regions
- Photons: $30 < p_T^\gamma < 400$ GeV with $|\eta| < 1.0$
- Jets (cone with R=0.7): pT > 15 GeV and $|\eta|<0.8$ or $1.5<|\eta|<2.5$
- Dominant production at $p_T^\gamma < 120$ GeV is through Compton scattering: $qg \to \gamma q$
- Various rapidity regions ⇒ various parton x and qg fractions.





Inclusive photon+jet production

- Cross section is directly proportional to PDFs in a given (x,Q^2)
- Probe PDFs in the range

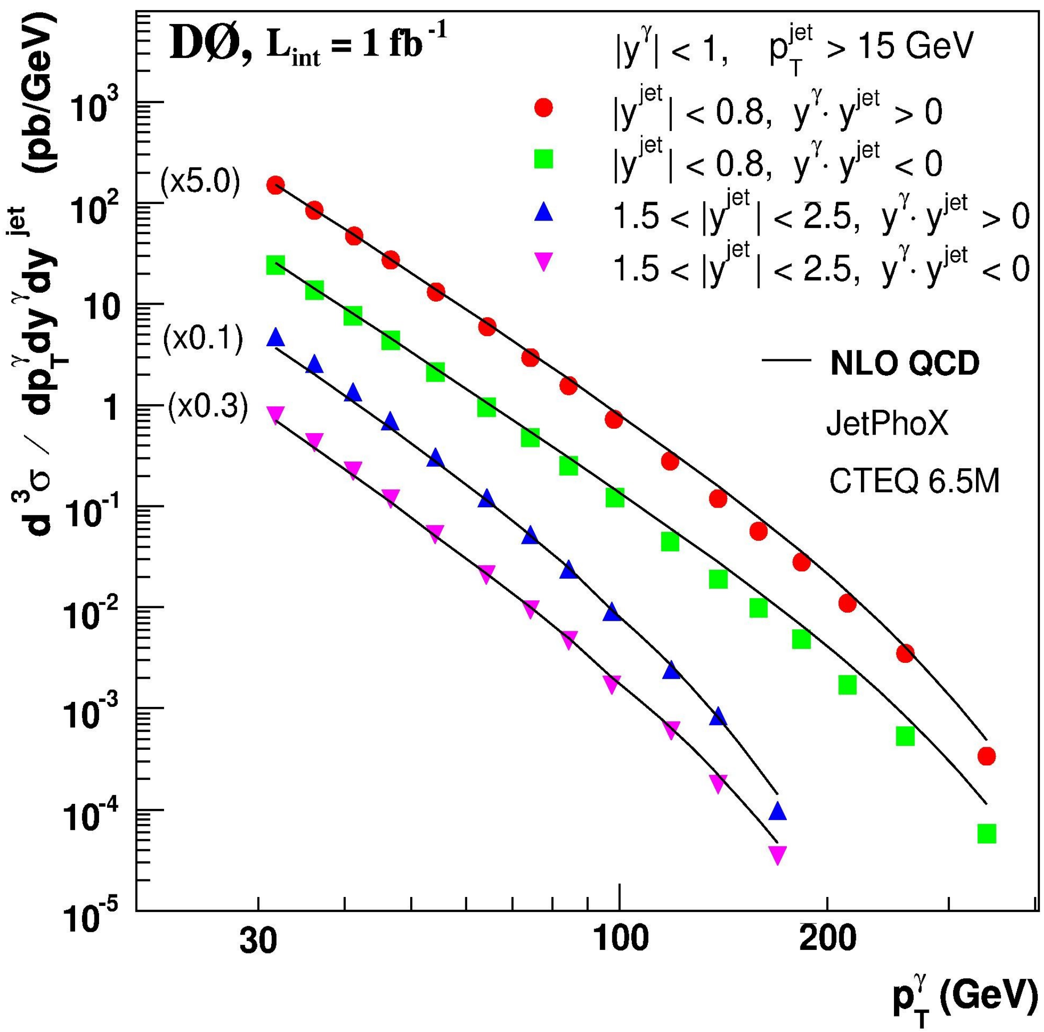
$$0.007 \le x \le 0.7 \text{ and } 900 \le Q^2 \le (0.4 - 1.0)\times 10^5 \text{ GeV}^2$$

Triple differential cross section

- Cross section results are shown with stat.+syst. uncertainties
- Analytical unfolding is applied to remove detector resolution effects

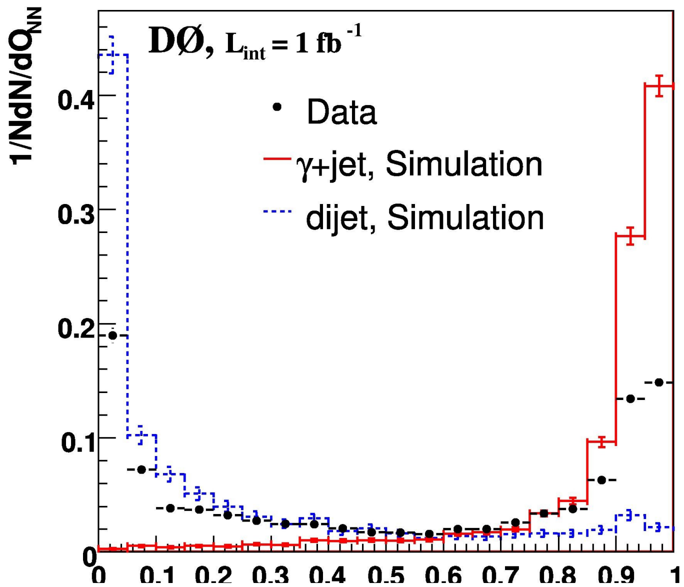
- Theory: JetPhoX (NLO QCD) with CTEQ6.5M and $\mu = \mu_f = \mu_F = p_T^\gamma f(y^*)$

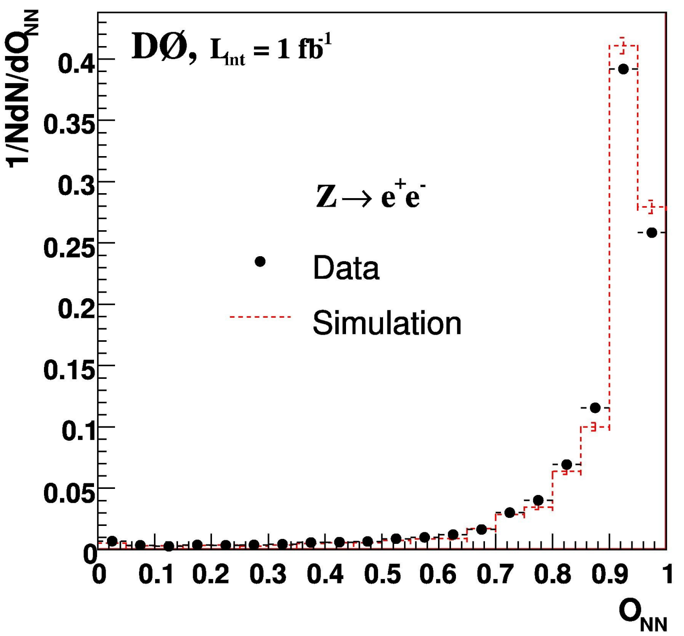
$$f(y^*) = \sqrt{\tfrac{1}{2}(1+\exp(-2y^*))}, \quad y^* = \tfrac{1}{2}(y^\gamma - y^{\text{jet}})$$



Inclusive photon+jet production

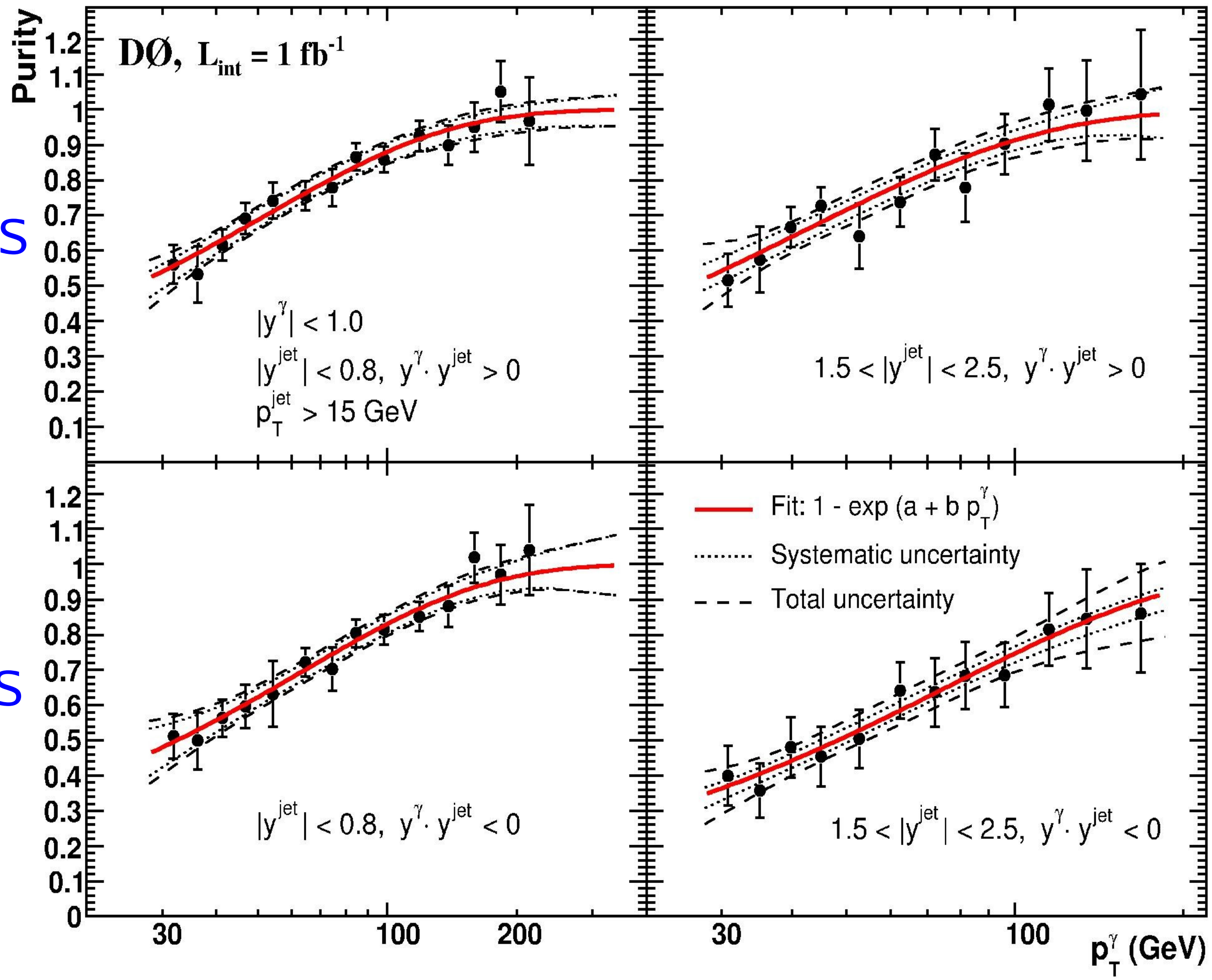
Photon ANN is used to determine photon purity in all the four rapidity regions





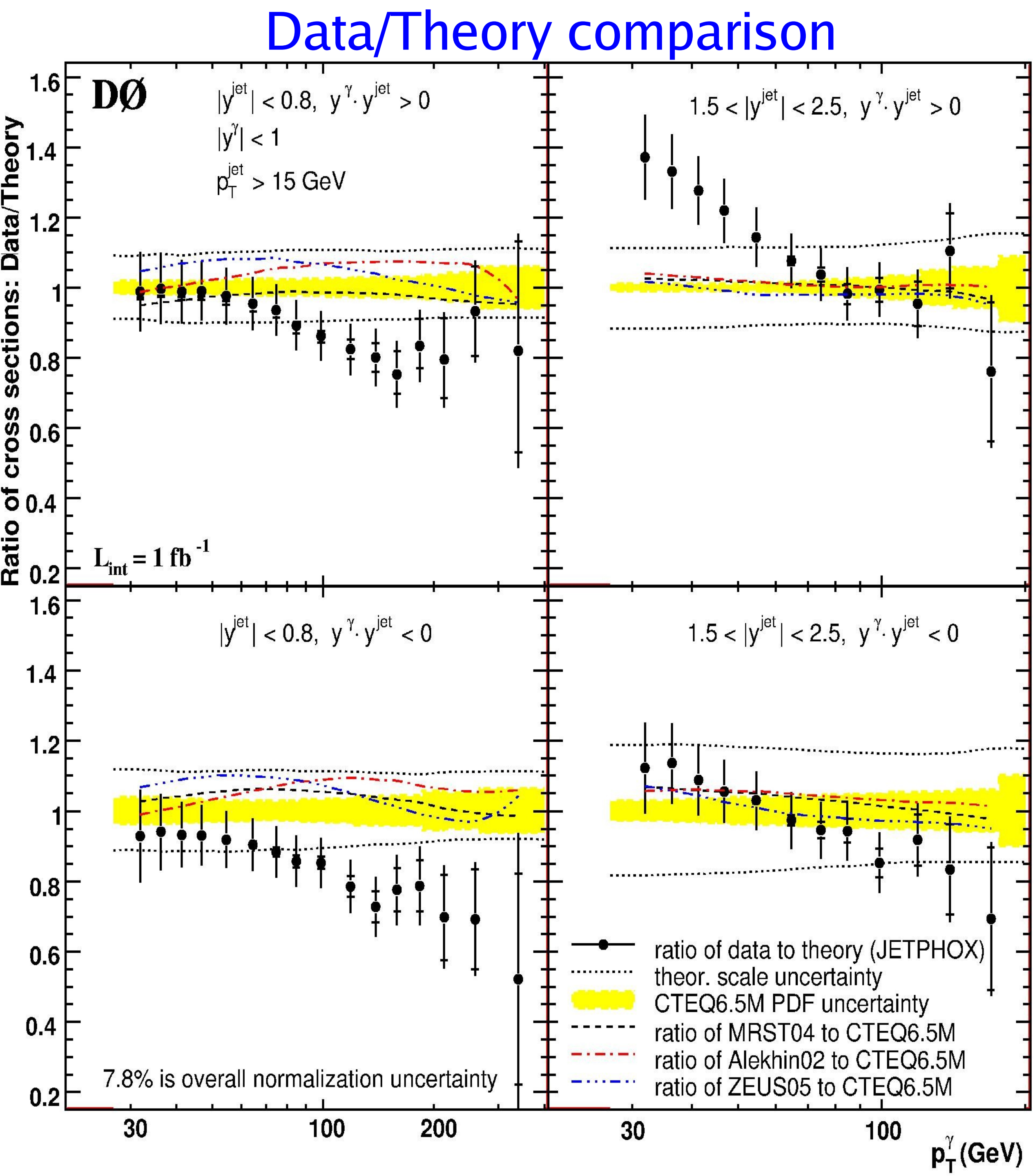
OS

SS



Central jets Forward jets

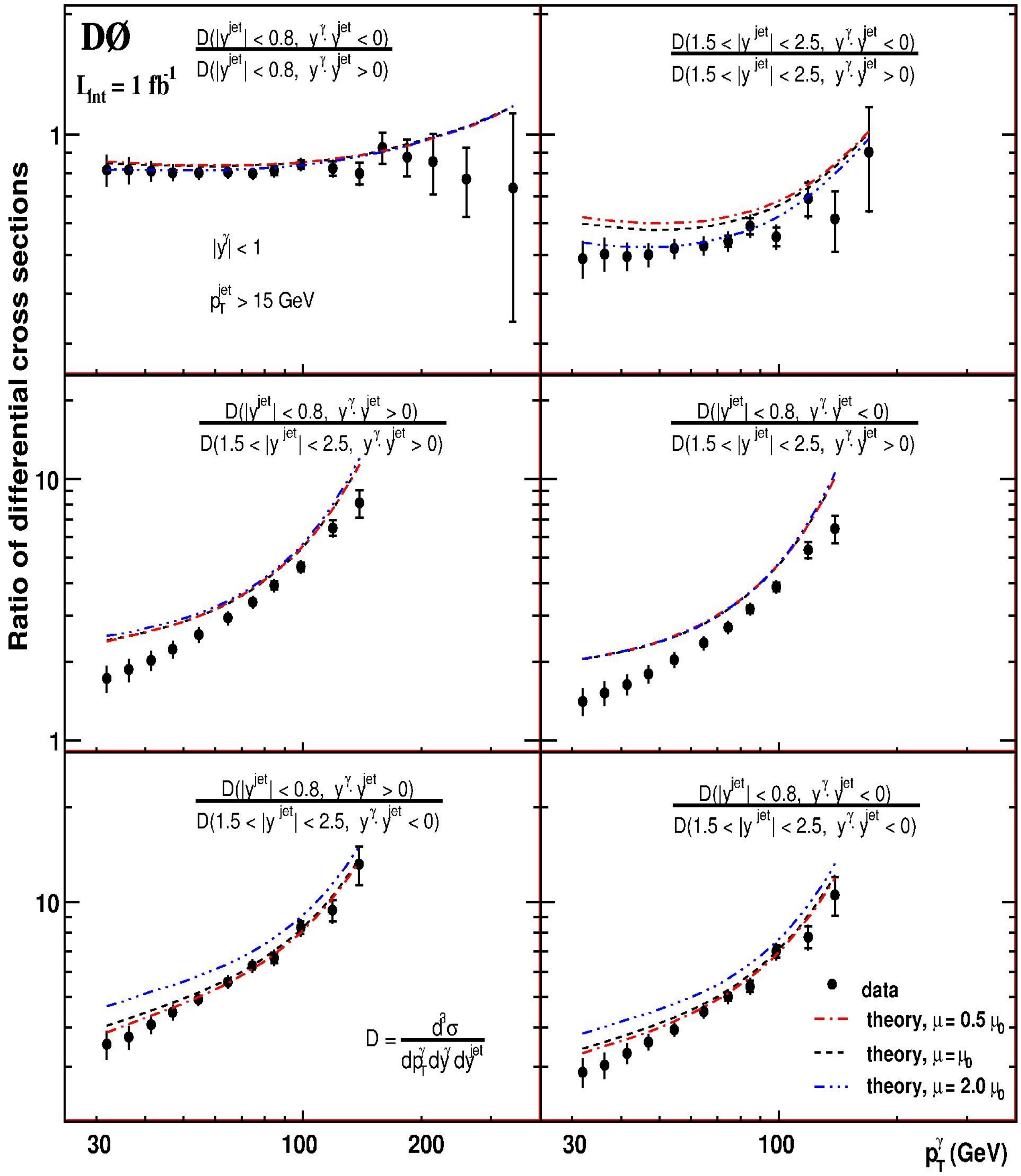
Inclusive photon+jet production



- ✓Theory does not describe shape of data in the whole measured region.
- ✓Deviation for central jets at $p_T^{\gamma} > 100$ GeV
- ✓Deviation for forward jets $(y^{\gamma}\, y^{jet} > 0)$ at $p_T^{\gamma} < 50$ GeV.
- ✓Structure similar to observed at UA2, CDF and D0 inclusive photons.

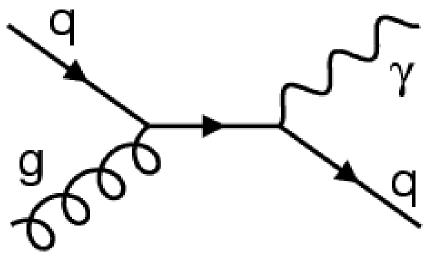
Inclusive photon+jet production

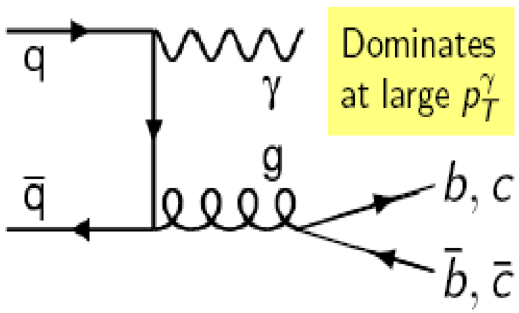
Cross section ratios between different regions



- ✓ Cross section ratio vs p_T^{γ} : *reduced systematics* (both data & theory)
- ✓ Shapes of measured cross section ratios in data *qualitatively reproduced* by theory in general
- ✓ But *quantitative disagreement* for some kinematic regions, in particular central jets over same rapidity side forward jets

Photon+ heavy flavor jet production





D0 Collab., Phys.Rev.Lett. 102, 192002 (2009)

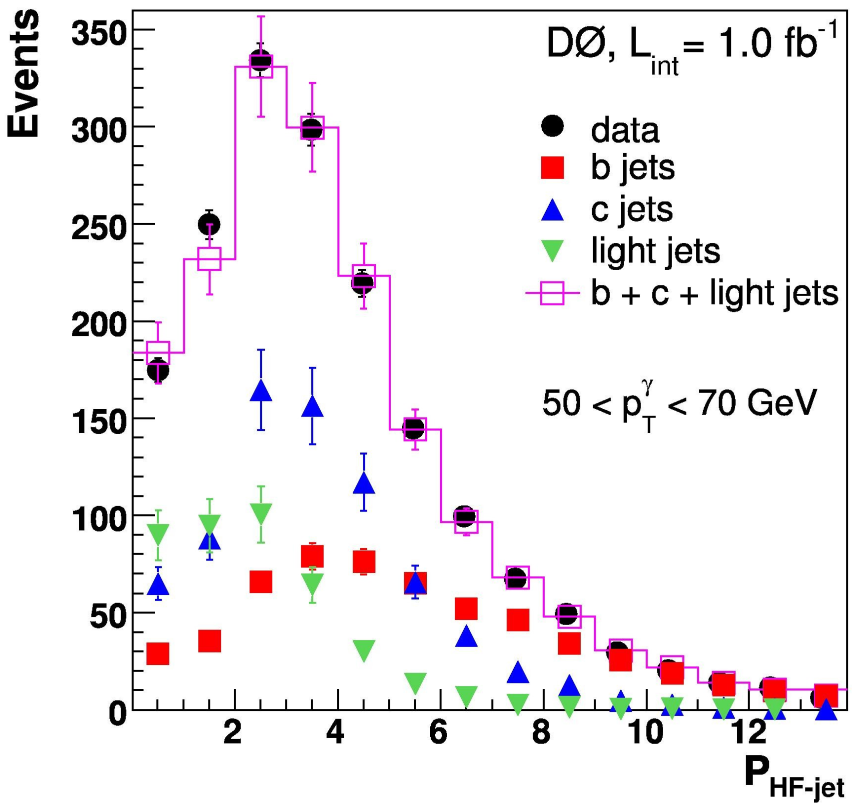
- QCD Compton-like scattering dominates for b(c) production up to 90(120) GeV
- Outgoing = incoming quark

⇒ Constraints on HF PDF

$p\bar{p} \to \gamma + b, c$ jet: Event selection

- $p_T^\gamma > 30$ GeV (up to 150 GeV), $|y^\gamma| < 1.0$
- Isol< 0.07, frac$(EM) > 0.96$, $\mathcal{O}_{NN}(\gamma) > 0.7$
- $\not{E}_T < 0.7 p_T^\gamma$ (cosmics, $W \to e\nu$)
- $p_T^{jet} > 15$ GeV, $|y^{jet}| < 0.8$, $(R_{jets} = 0.5)$
- Leading jet: $N_{Track} \geq 2$, $\mathcal{O}_{NN}(HF) > 0.85$

2 regions: $y^\gamma \cdot y^{jet} > 0$, $y^\gamma \cdot y^{jet} < 0$

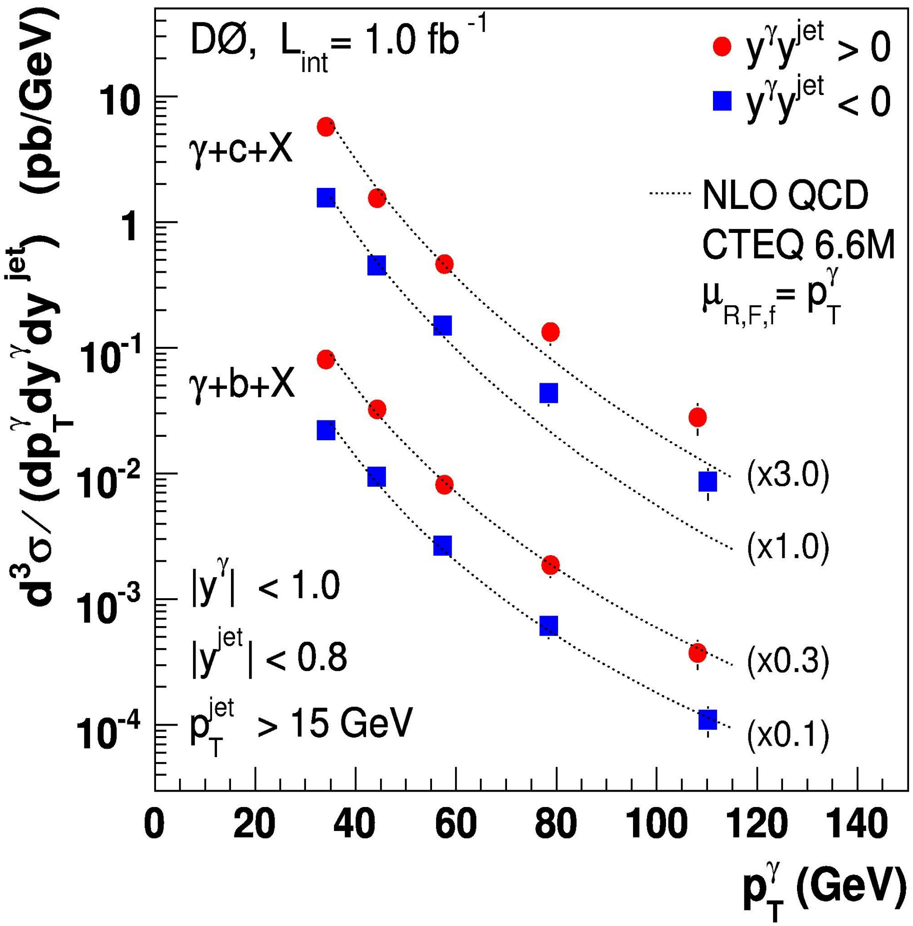


- Fitting $P_{HF\text{-}jet} = -\ln \prod_i \mathrm{Prob}^i_{track}$ templates of b, c (MC) and light jets (data) to shape of data

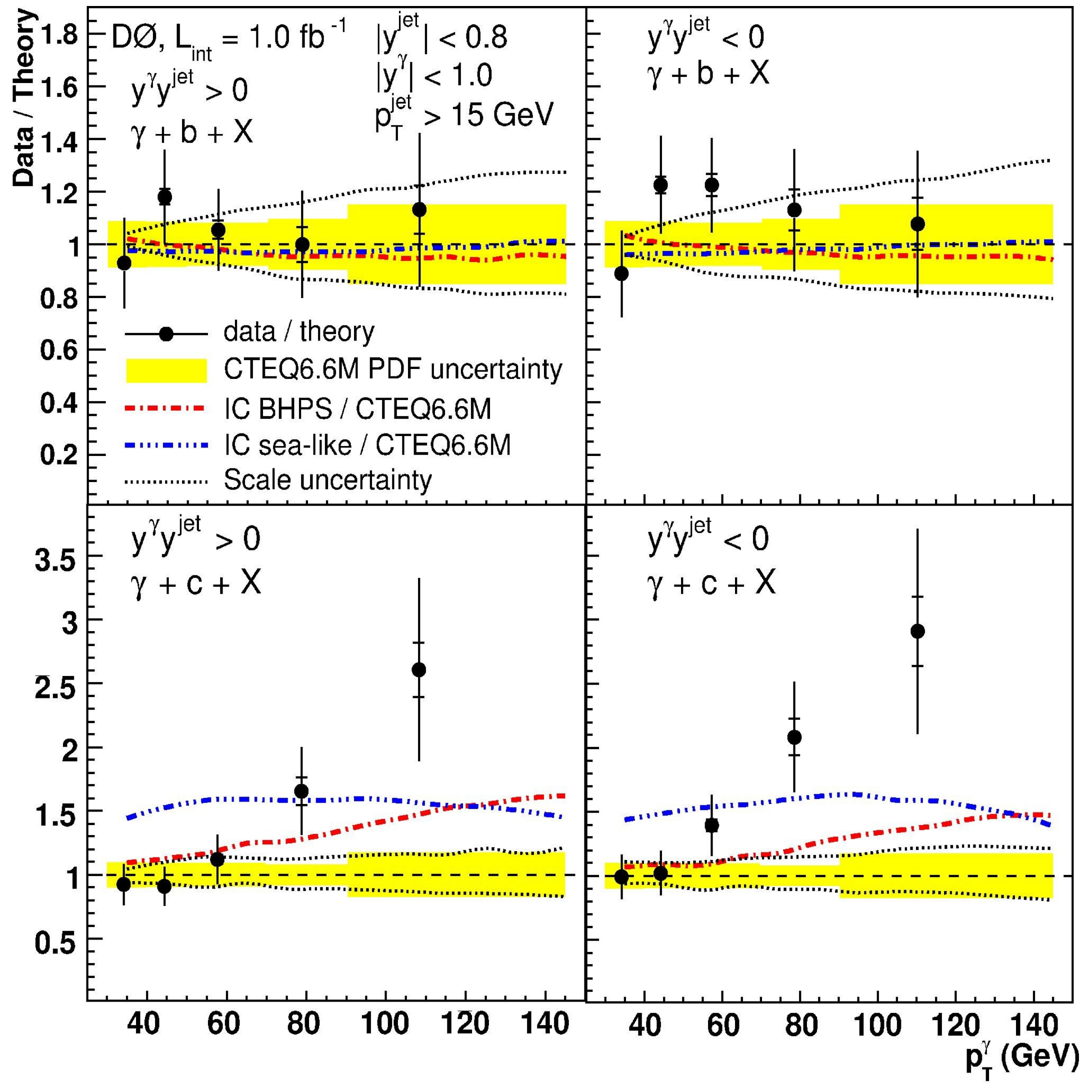
Photon+ heavy flavor jet production

Triple differential cross section

- Plotted: p_T^γ-weighted bin centres
- $P_{HF-\text{jet}}$ fit in each bin
- For $\gamma + b + X$ and $\gamma + c + X$
- In two regions $y^\gamma \cdot y^{\text{jet}} > 0$ and $y^\gamma \cdot y^{\text{jet}} < 0$



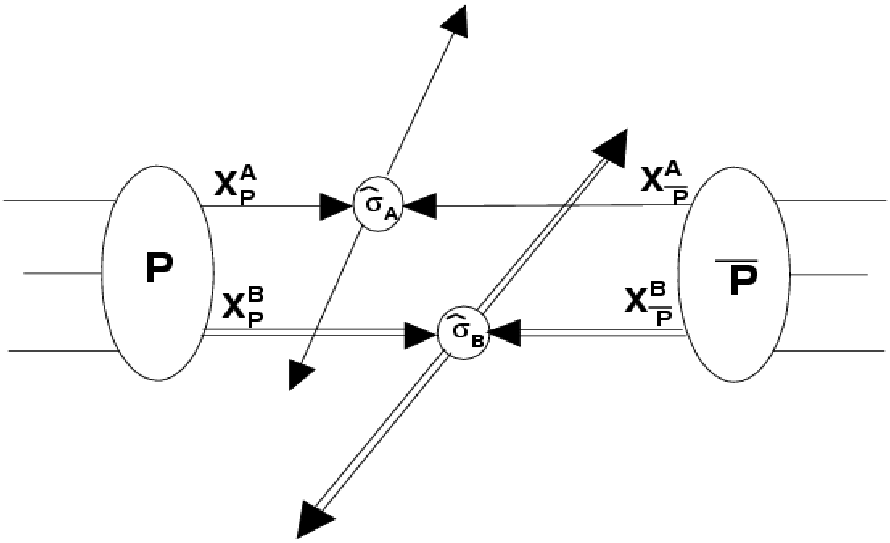
Data/theory comparison



- γ+b cross section agrees in the whole range
- γ+c cross section disagrees at p_T^γ > 70 GeV

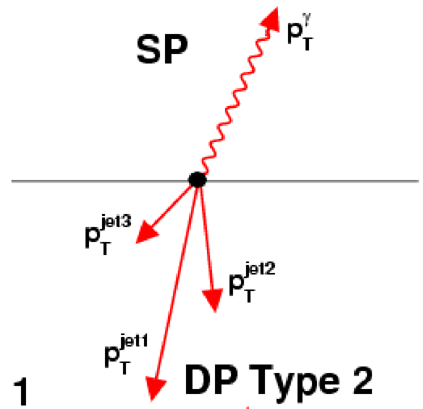
Double Parton Scattering in γ+3 jet events

- Complementary information about proton structure: Spatial distribution of partons
  ⇒ Possible parton-parton correlations. Impact on PDFs?
- Needed for understanding many signal events and correct estimating backgrounds to many rare processes.
- Especially important at high luminosities due to additional pp(bar) interactions.



Selections: 60 < photon pT < 80 GeV, lead. jet pT > 25, other 2 jets with pT > 15 GeV

Main Background: Single Parton scattering



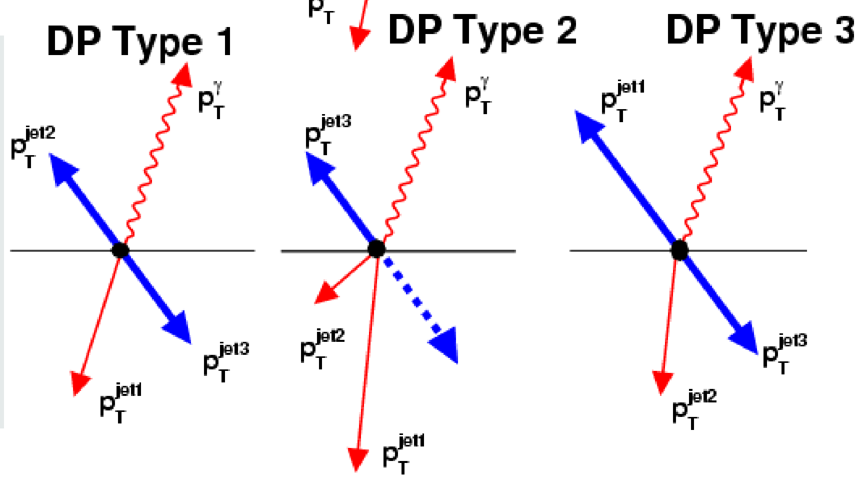
$$\sigma_{DP} = m \cdot \sigma_A \cdot \frac{\sigma_B}{2\sigma_{eff}}$$

σ_A, σ_B: cross sections of processes A, B

σ_{eff}: characterising size of effective interaction region

$\sigma_B/2\sigma_{eff}$: prob. of 2nd interaction, given 1st one

($m = 2(1)$ when A and B are (not) distinguishable)



Discriminating variables

$$S_\phi = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{\Delta\phi(\gamma,i)}{\delta\phi(\gamma,i)}\right)^2 + \left(\frac{\Delta\phi(j,k)}{\delta\phi(j,k)}\right)^2}$$

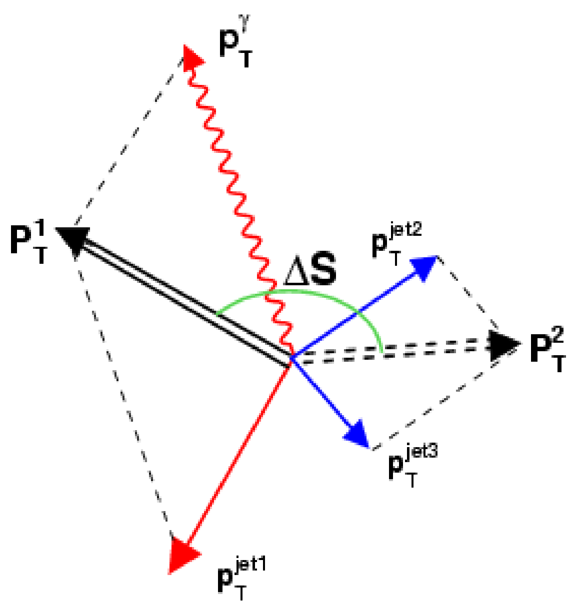
$$S_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|\vec{P_T}(\gamma,i)|}{\delta P_T(\gamma,i)}\right)^2 + \left(\frac{|\vec{P_T}(j,k)|}{\delta P_T(j,k)}\right)^2}$$

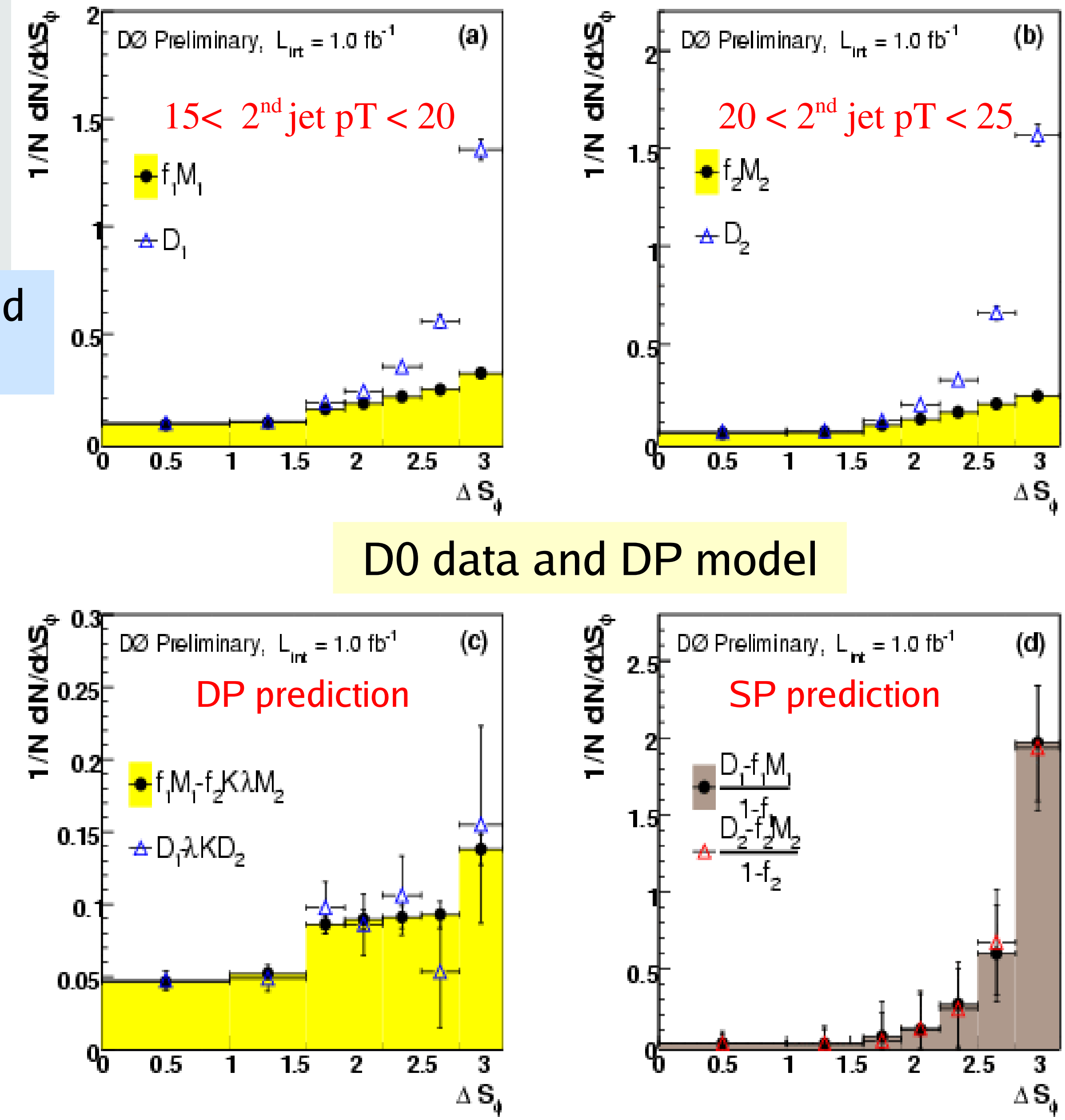
$$\Delta S = \Delta\phi(p_T^{\gamma,\,\mathrm{jet}}, p_T^{\mathrm{jet}_i,\,\mathrm{jet}_k})$$

Computed for pair with minimum S

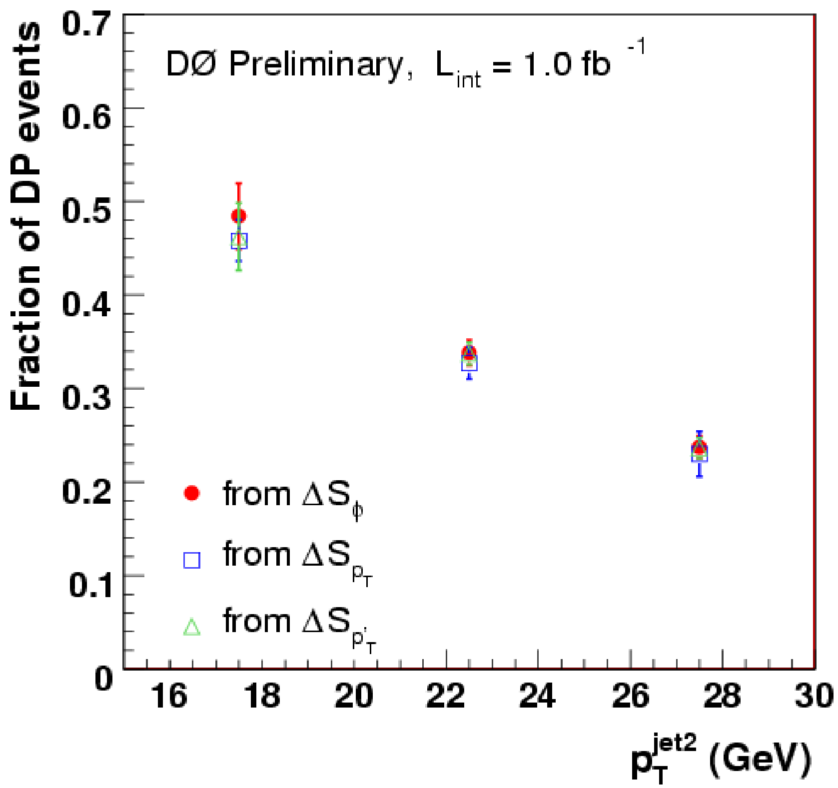
>95% of signal DP events are minimized by pairs (γ, jet1) and (jet1, jet3)

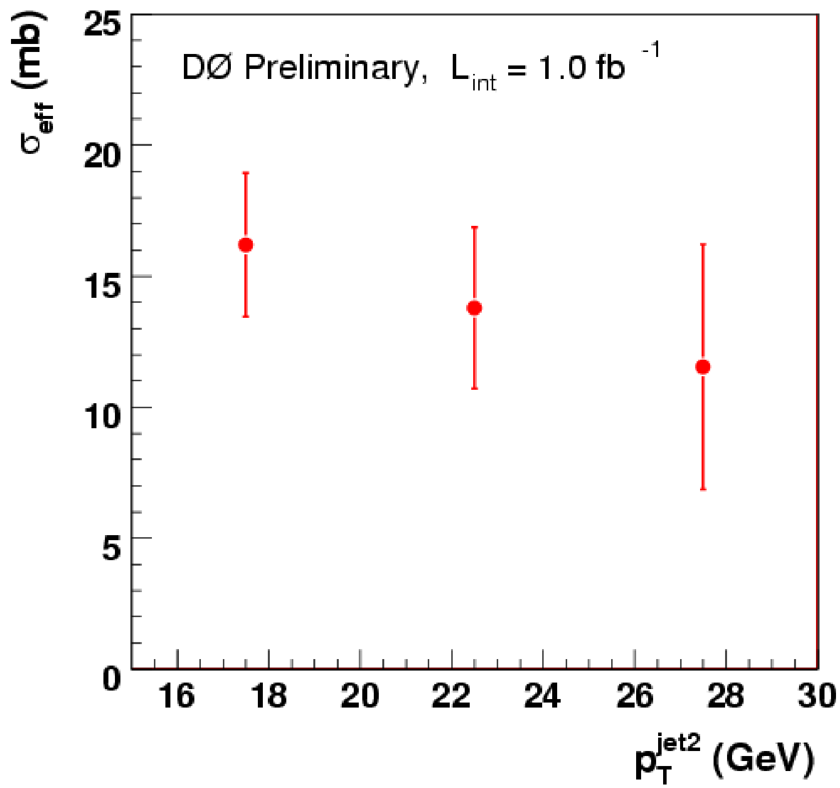
- Measurement is done in three bins of 2nd jet pT: 15-20, 20-25 and 25-30 GeV
- Data-driven technique: since dijet pT spectrum is steeper than that for radiation jets the DP fractions should drop for larger jet pT.





DP fractions and effective cross section





- The measured DP fractions drop from 0.47 ± 0.04 at 15 < 2nd jet pT < 20 GeV to 0.23 ± 0.03 at 25 < 2nd jet pT < 30 GeV.

- Effective cross section is varied for the same bins as 16.2 ± 2.8 mb to 11.5 ± 4.7 mb and agree for all jet pT bins within uncertainties. Systematic uncertainties have negligible bin-to-bin correlations. Averaging over pT bins gives

$$\sigma_{eff}^{aver} = 15.1 \pm 1.9 \text{ mb}$$

- Good agreement with two previous Run I measurements by CDF ("4 jets", $\sigma_{eff} = 12.1^{+1.7}_{-2.3}$ mb and "γ+3jets", $\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb)

Summary

- Tevatron and D0 are performing well

- Inclusive photon production cross section $d^2\sigma/dp_T^{\gamma}d\eta^{\gamma}$ Published
  - In agreement with theory
  - Data/Theory shape is similar to UA2 and CDF (Run I); still needs to be understood

- Photon+jet production cross section $d^3\sigma/dp_T^{\gamma}d\eta^{\gamma}d\eta^{jet}$ Published
  - Four γ-jet rapidity regions
  - Ratios of cross section between regions
  - Some deviations from theory predictions observed

- Photon+HF jet production cross section Published
  - γ+b cross section is in agreement with theory
  - γ+c cross section does not agree with theory at $p_T^{\gamma} > 70$ GeV

- Double parton interactions in γ+3 jet events Preliminary
  - Measured DP fractions in three bins of $p_T^{2\text{nd}\ jet}$
  - Measured effective cross section in the same bins
  - Good agreement with CDF (Run I) measurements.